From Pencil Lead to Relativistic Quantum Physics

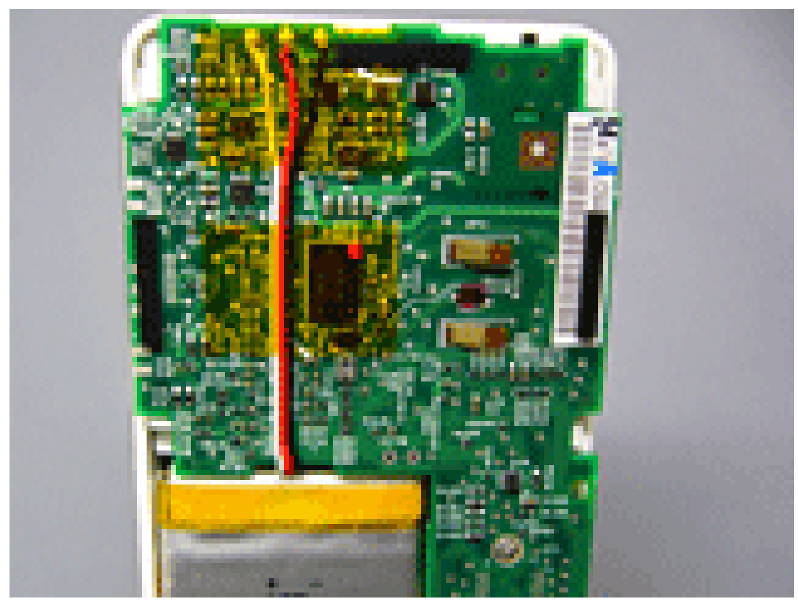
or

Electronic phenomena in mesoscopic structures

- Lecture #1: Overview
- Lecture #2: Quantum Transport in Solids
- Lecture #3: Quantum Theory of Graphene

Why Study Electronic Materials and Devices?

1. The Practical



Why Study Electronic Materials and Devices?

2. The Fundamental

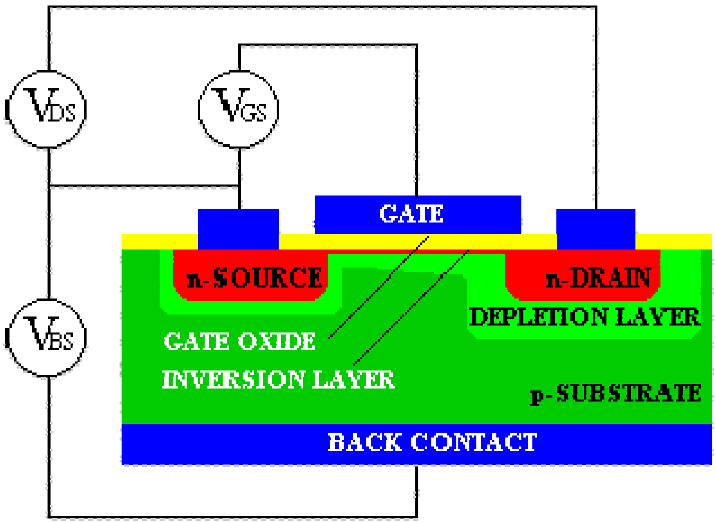
A laboratory for the study of quantum many body physics

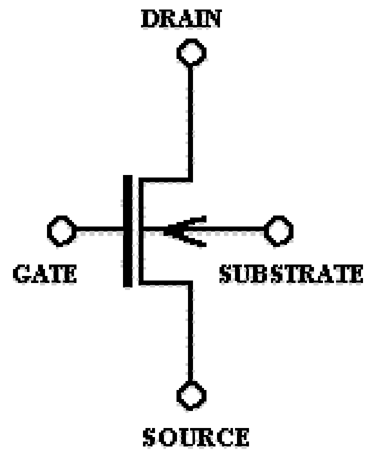
- Collective behavior
- Symmetry breaking
- Role of electron electron interactions
- Role of disorder
- Emergent low energy behavior:
  - emergent “quasiparticles”
  - topological order

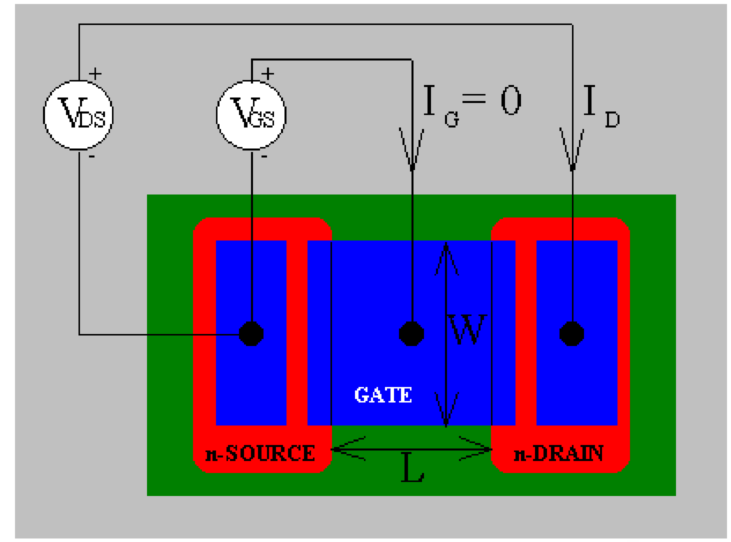
The Transistor

Bardeen, Brattain, Shockley, 1947
Nobel Prize 1956

Field Effect Transistor



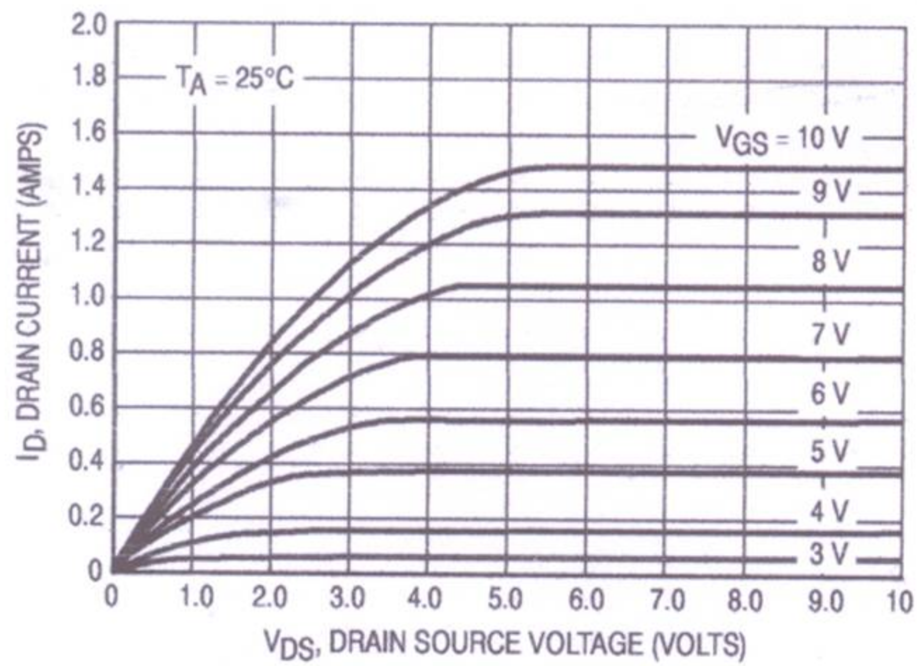




MOSFET:

Metal-Oxide-Silicon
Field Effect Transistor

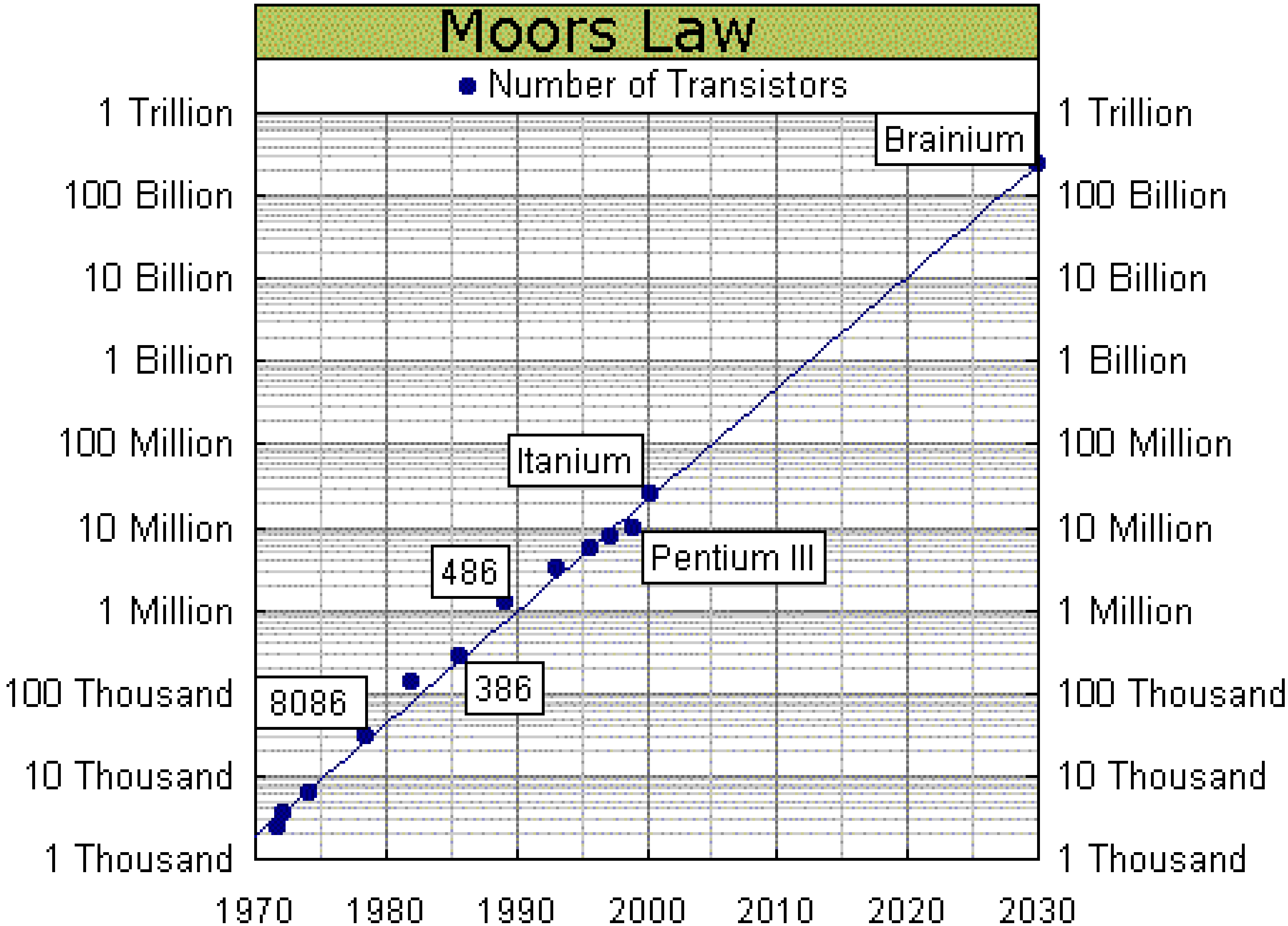
A faucet for electrons



Moore's Law

The number of transistors on a chip doubles approximately every two years

Optimistic?

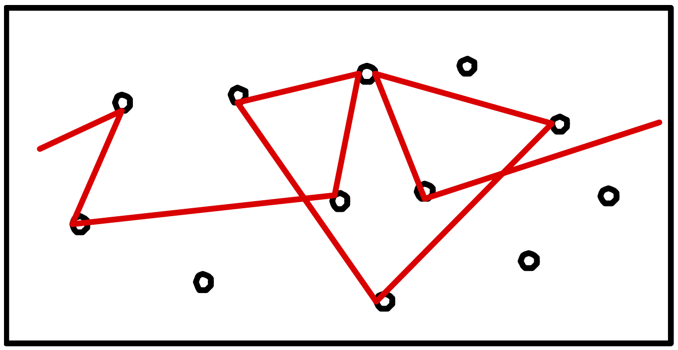


Moors Law
Number of Transistors
1 Trillion
100 Billion
10 Billion
1 Billion
100 Million
10 Million
1 Million
100 Thousand
10 Thousand
1 Thousand
Brainium
Itanium
Pentium III
486
386
8086
1970
1980
1990
2000
2010
2020
2030

Macroscopic: big things

Classical physics dominates:

~ 1 cm



$V = IR$; $R = \rho L/A$;

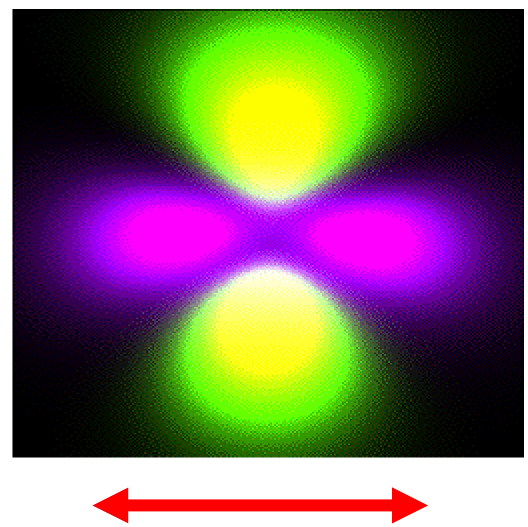
Drude model: electrons ~ billiard balls

$\rho \sim m/(ne^2\tau)$

Microscopic: atoms & molecules

Quantum physics dominates:

$$H \Psi_n = E_n \Psi_n$$



~ 1 Å = 10^{-8} cm

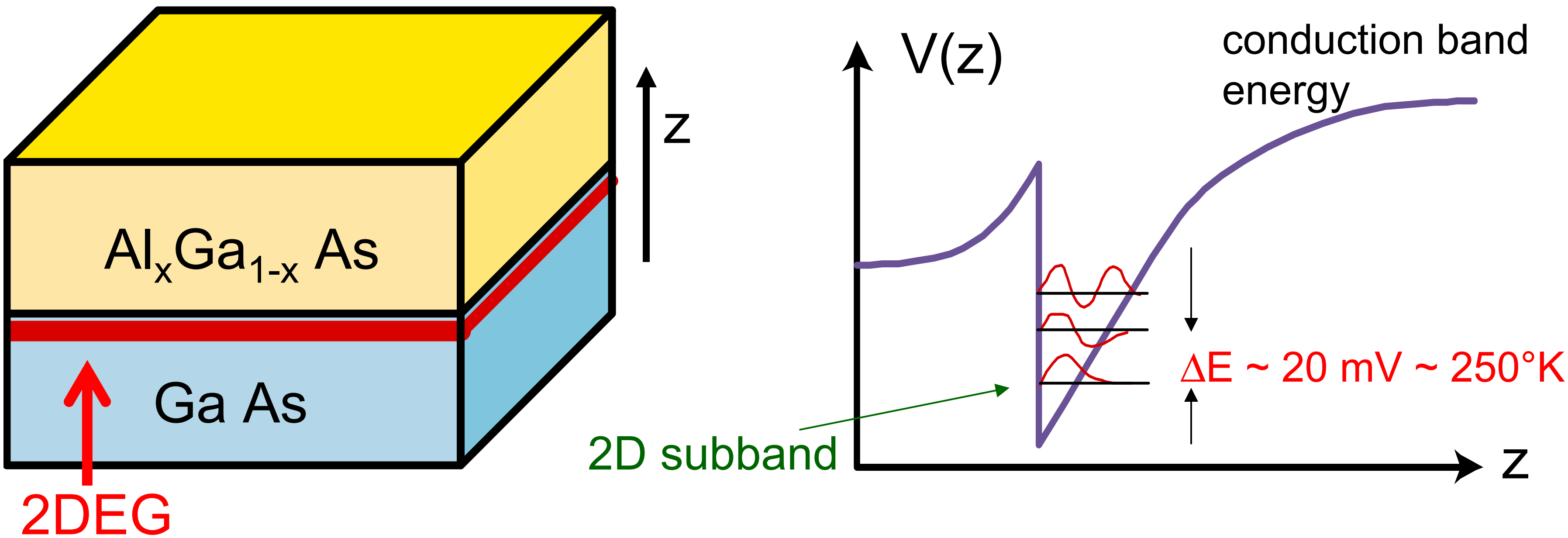
Mesoscopic

- Many atoms, but quantum physics plays a fundamental role
- Quantum effects are important for systems smaller than the thermal decoherence length $L < L_\varphi(T)$
- Small size OR Low temperature

Flatland ... (1980's)

Semiconductor Heterostructures : "Top down technology"

→ Two dimensional electron gas (2DEG)

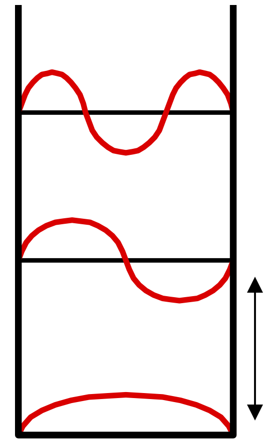


Fabricated with atomic precision using MBE.

1980's - 2000's : advances in ultra high mobility samples

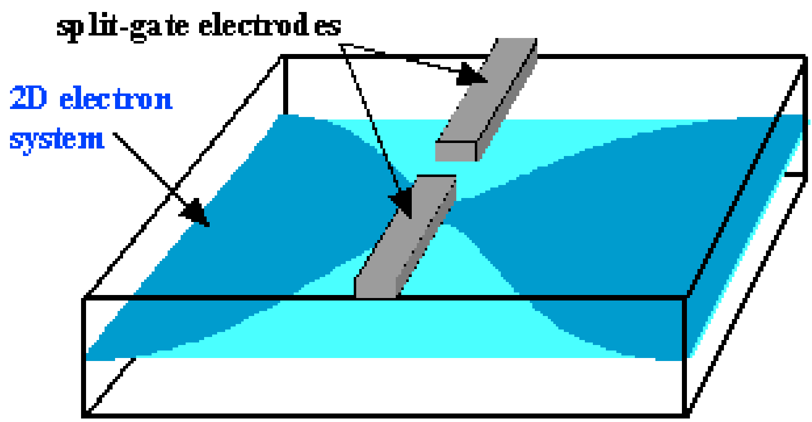
2D to 1D : Quantum Wires (1990's):

1D for E < ΔE: the 1D subband spacing



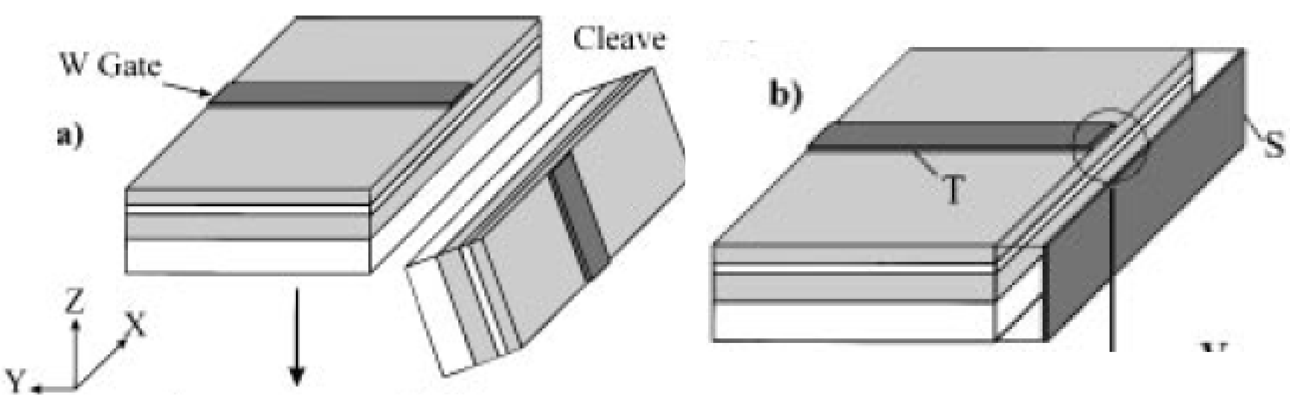
$$\Delta E \sim \frac{\hbar^2}{2m^* L^2}$$

1. Split Gate Devices: (Tarucha et al. 95)



ΔE ~ 5 meV

2. Cleaved Edge Overgrowth (Yacoby et al. 96)

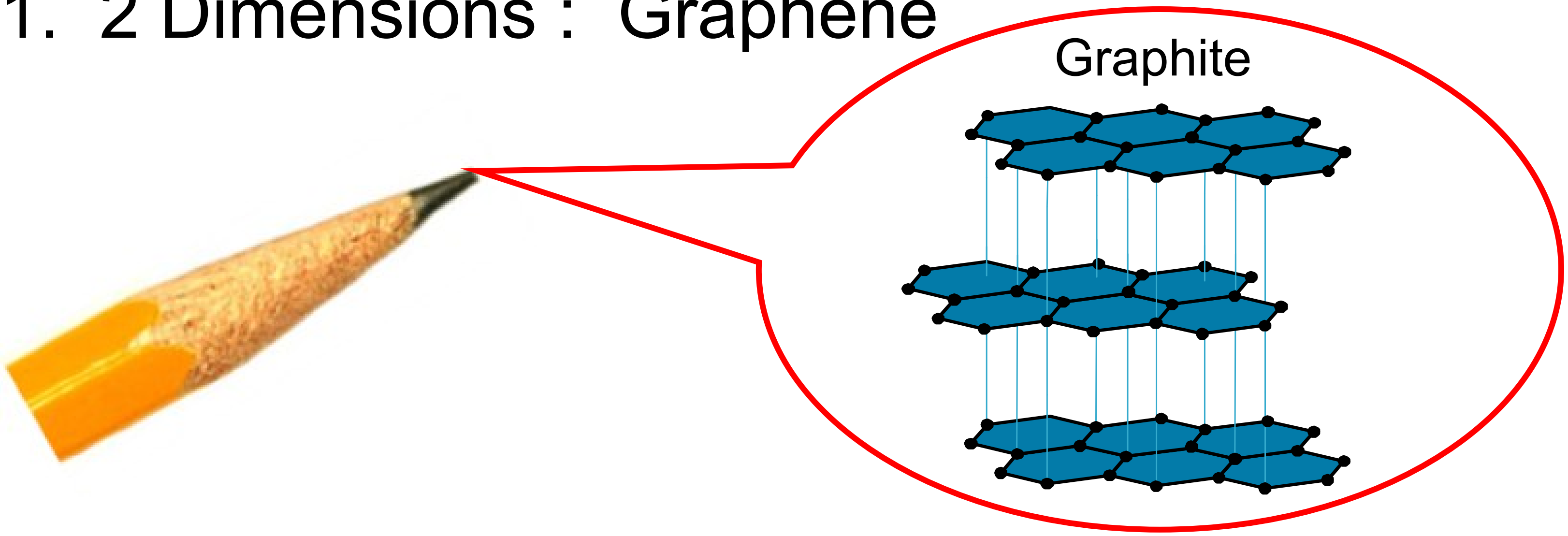


ΔE ~ 20 meV

Molecular scale confinement (1990's-2000's)

"Bottom up technology"

1. 2 Dimensions : Graphene



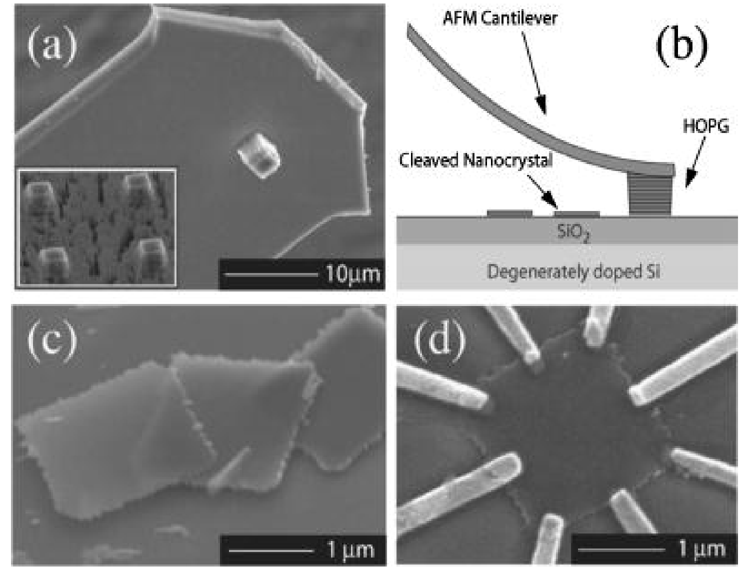
- Graphene = single layer of graphite

  A unique 2D electronic material
- Structural Rigidity due to strong in plane bonds
- Electrical Conductivity due to π electrons
- Purely 2 Dimensional at room temperature

Isolating Single Planes of Graphene

Philip Kim (Columbia)
Zhang et al. APL 2004

"Nanopencil" on AFM cantilever deposits ~ 15 layer graphite films



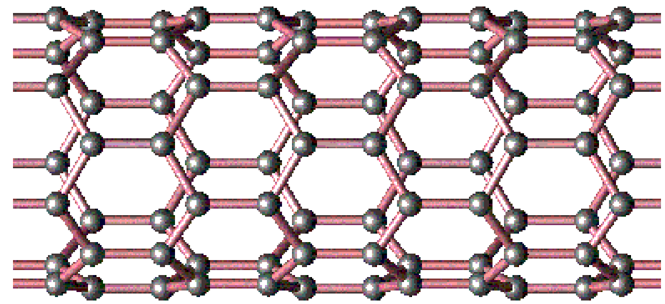
Andre Geim (Manchester)
Novoselov et al. Science 2004

Individual layers on SiO_2 prepared by mechanical exfoliation.

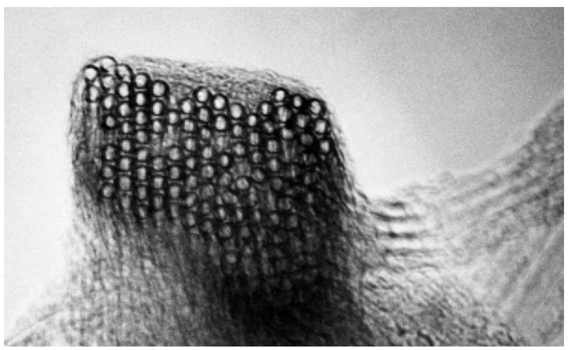
SEM

2. 1 Dimension : Carbon Nanotubes

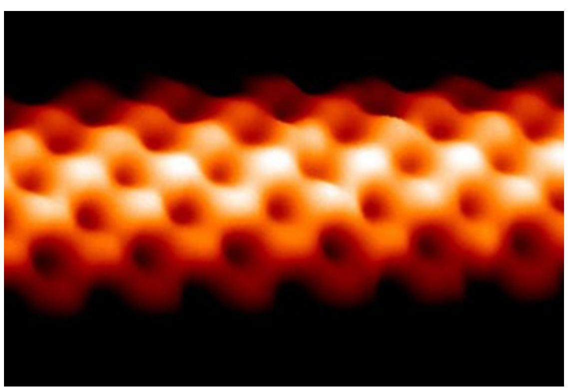
Graphene wrapped
into a cylinder



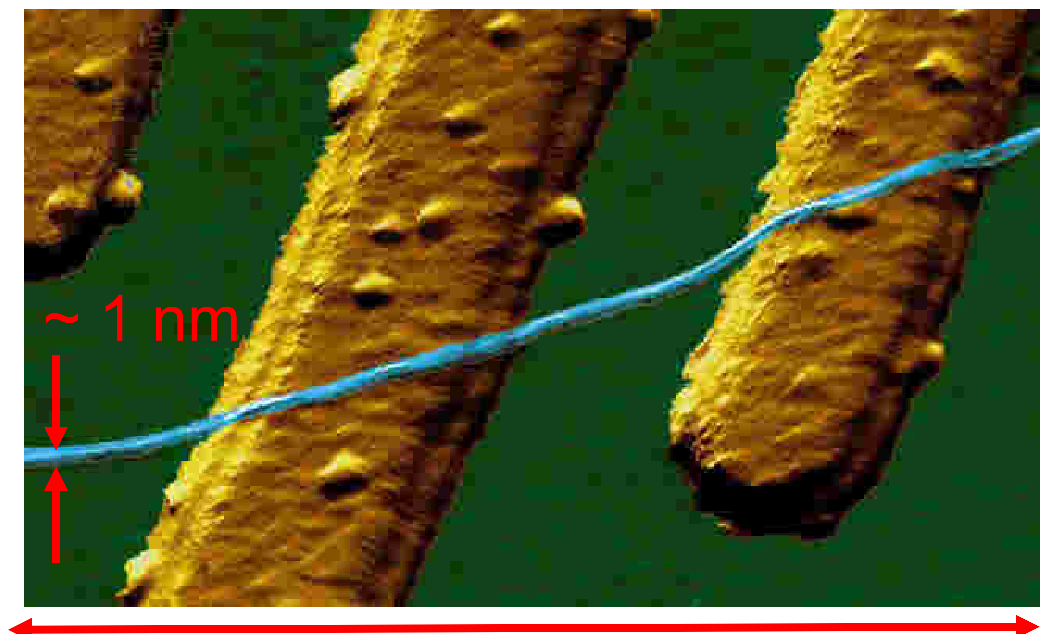
A Molecular Quantum Wire
$\Delta E \sim 1$ eV $\sim 10^4$ K



"rope" TEM



single tube STM

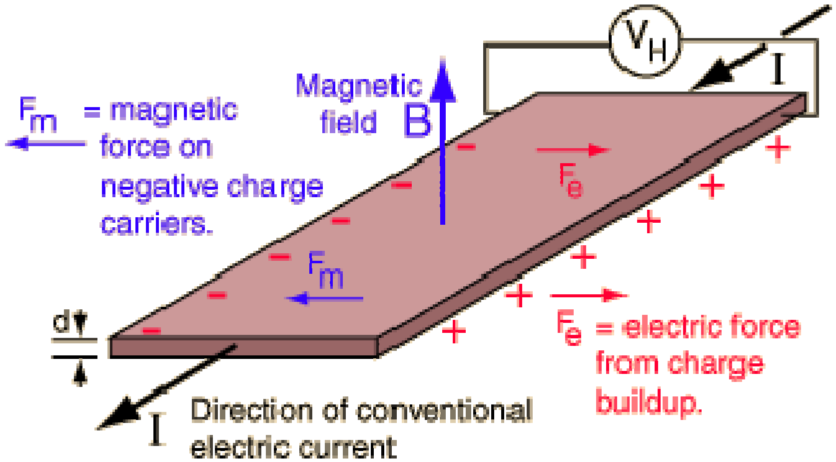


~ 1 μm

AFM

The Hall Effect

A tool for characterizing an electronic device



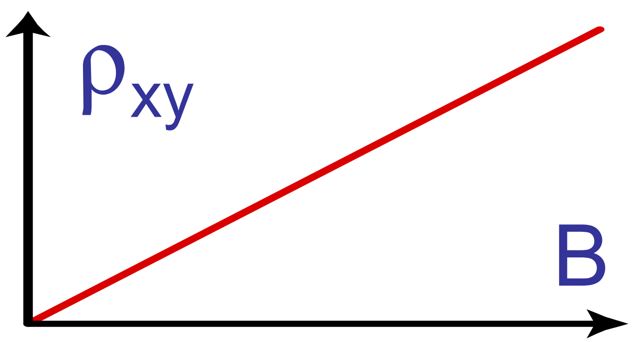
Force: $\vec{F} = \vec{F}_e + \vec{F}_m = q(\vec{E} + \vec{v} \times \vec{B})$

Electric Field (F_y=0): $E_y = v_x B_z$

Current density: $J_x = nqv_x$

q = charge of carrier

n = carrier density



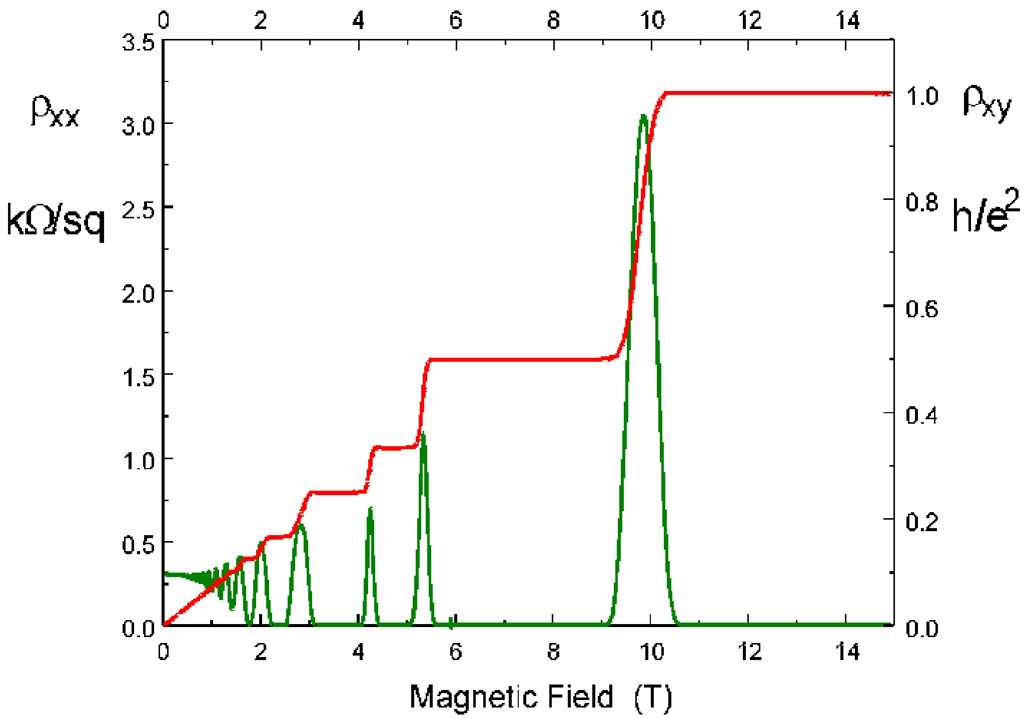
Hall Conductivity $\rho_{xy} = \frac{E_y}{J_x} = \frac{B}{nq}$

The Hall conductivity measures

- The density of the mobile charge carriers
- The sign of the charge carriers (e<0!)

The Quantized Hall Effect

Hall effect in 2DEG MOSFET at large magnetic field

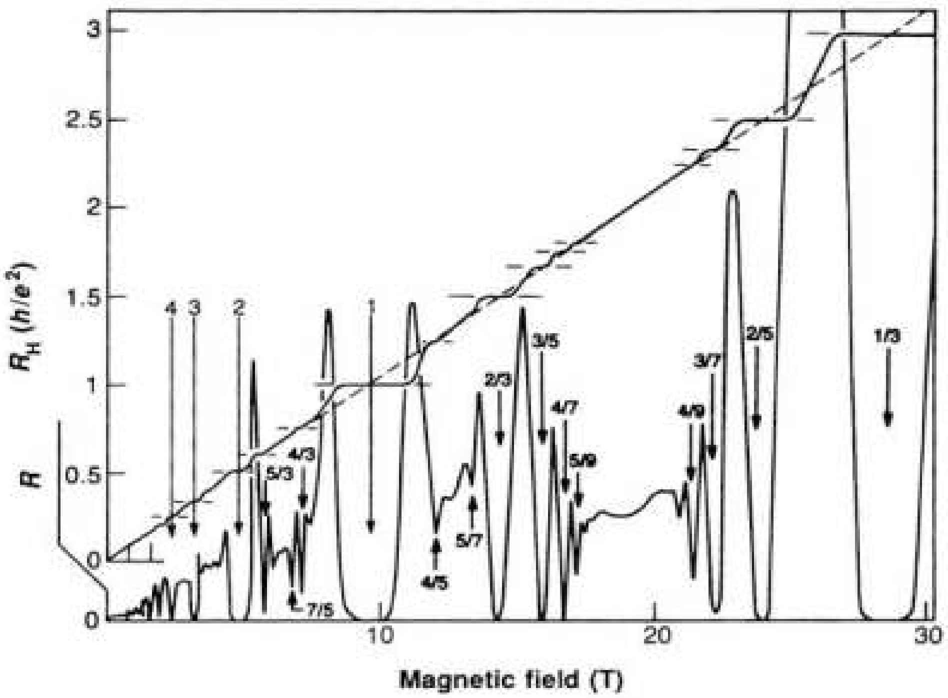


Von Klitzing,1981 (Nobel 1985)

- Quantization: $\rho_{xy} = R_Q / n$ n = integer accurate to 10^{-9} !
- Quantum Resistance: $R_Q = h / e^2 = 25.812\ 807\ \text{k}\Omega$
- Explained by quantum mechanics of electrons in a magnetic field

Fractional Quantized Hall Effect

Tsui, Stormer and Gossard 1982



Stormer, Laughlin, Tsui
1998 Nobel Prize

- Higher Magnetic fields, Higher quality samples
- Quantization: $\rho_{xy} = (p/q)R_Q$
- Explained by Laughlin (1982):
  - Collective behavior of a “quantum fluid”
  - Emergent “quasiparticles” with fractional charge e/q

Next Time:
Quantum Transport in Solids

- Waves and particles in quantum mech.
- Quantization in atoms
- Metals vs Insulators : Energy gap
- Emergent particles in a solid
- Landau quantization in a magnetic field and the quantum Hall effect